ON THE RELATIONSHIPS BETWEEN SELF-REPORTED BICYCLING INJURIES AND PERCEIVED RISK AMONG CYCLISTS IN QUEENSLAND, AUSTRALIA

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ABSTRACT

The focus of governments on increasing active travel has motivated renewed interest in cycling safety. Bicyclists are up to 20 times more likely to be involved in serious injury crashes than drivers so understanding the relationship among factors in bicyclist crash risk is critically important for identifying effective policy tools, for informing bicycle infrastructure investments, and for identifying high risk bicycling contexts.

This study aims to better understand the complex relationships between bicyclist self reported injuries resulting from crashes (e.g. hitting a car) and non-crashes (e.g. spraining an ankle) and perceived risk of cycling as a function of cyclist exposure, rider conspicuity, riding environment, rider risk aversion, and rider ability.

Self reported data from 2,500 Queensland cyclists are used to estimate a series of seemingly unrelated regressions to examine the relationships among factors. The major findings suggest that perceived risk does not appear to influence injury rates, nor do injury rates influence perceived risks of cycling. Riders who perceive cycling as risky tend not to be commuters, do not engage in group riding, tend to always wear mandatory helmets and front lights, and lower their perception of risk by increasing days per week of riding and by increasing riding proportion on bicycle paths. Riders who always wear helmets have lower crash injury risk. Increasing the number of days per week riding tends to decrease both crash injury and non crash injury risk (e.g. a sprain). Further work is needed to replicate some of the findings in this study.

BACKGROUND AND RESEARCH AIMS

Cycling provides substantial health, environmental and economic benefits. Physical activity is associated with reduced risk of cardiovascular disease, diabetes, cancer and obesity *(1)*. Achieving mode shift from private vehicles to active transport would also reduce greenhouse gas emissions of which approximately half are transport-related *(2)*. Recent Australian research found that current levels of cycling participation have a value of \$227m per annum to the health system and provide a financial benefit of \$63.9m per annum through congestion reduction *(3)*.

While cycling has many benefits, injuries are a significant concern. Despite low levels of cycling participation by international standards *(4)*, pedal cyclist deaths comprised about 2% of road fatalities in both the United States *(5)* and Australia *(6)* in 2009. The number of pedal cyclists sustaining injuries with high threat to life in Australia has increased from 523 in 2000-01 to 917 in 2007-08, accounting for 10% of all road users in this category *(7)*. The crash risk of bicycle riding varies among jurisdictions, being lower in those countries where cycling participation rates are higher *(4)*. While rates are not available for Australia, the death and injury rate for police-reported on-road crashes per distance travelled for bicycle riders was 11 times higher than for car drivers in New Zealand *(8)* and 14 times higher in Great Britain *(9)*. In the United Kingdom cyclists are 20 times more likely to be admitted to hospital per trip than car occupants *(10)*.

On-road cycling crash injuries are under-reported in police data, with hospital data showing two to three times as many injured cyclists *(11-14)*. In addition, official crash data does not include many potentially important factors, including exposure data. For this reason, many of the studies of cyclist crash risk have used self-reported data from surveys. However, survey data has its drawbacks since respondents often ride further than the average rider *(15)*, are more likely to ride road bikes and most self-reported crashes are of low severity and so the relative importance of factors contributing to their occurrence may differ from more severe crashes.

While the quality and completeness of data regarding crash injuries to cyclists has been criticised, even less is known about non-crash injuries. A survey of members of Bicycle Queensland *(16)* noted that 31% of respondents had at least one cycling injury in the previous 12 months and that the main cause of the most severe cycling injury was "falling off" for 25.6% of these injuries. Among adult cyclists surveyed in Kansas *(17)*, 10.1% of injuries were sprains, a type of injury that is likely to result from a non-crash event. Prolonged postural adaptations and repetitive limb movements can contribute to lower limb and lower body problems for cyclists *(18)*, including knee pain, back pain, as well as vascular and neurological problems (leg, perineum and hands). Injuries are associated with incorrect saddle positioning and the position of the foot in relation to the pedal. A review of mountain biking injuries *(19)* concluded that perineal numbness due to nerve compression is common and vascular problems and pretibial lacerations from the chain ring teeth have also been reported. Overuse injuries comprised 48% of reported injuries in a recreational long-distance bicycle tour (the Cycle Across Maryland) and included pain (during motion or at rest), stiffness or swelling *(20)*. The body areas affected were the buttocks (34%), upper leg (25%), neck (24%), knee (24%), hands/fingers (19%), shoulder (17%), foot/toes (17%), back (16%), wrist (8%) and lower leg (6%). Self-reported pain in back, buttocks, upper leg and knee declined with age. Those that cycled less frequently (less than 26 miles per week) were more likely to sustain an overuse injury.

Studies examining factors affecting cyclist crashes have generally focused on the riding environment and rider characteristics.

Role of riding environment in crash risk

The term riding environment is used here to describe a range of characteristics such as the presence or absence of bicycle-specific facilities, speed limits, road surface characteristics and weather conditions affecting road surface (rain, snow and ice). A recent review *(21)* concluded that clearly-marked, bicycle-specific facilities (including cycle tracks at roundabouts, bike routes, bike lanes and bike paths) were safer than on-road cycling with traffic or off-road with pedestrians and other users. A number of studies have reported higher severities of injuries to bicycle riders in crashes with motor vehicles where vehicle speeds *(22)* or speed limits are higher (*23*) or the motor vehicle was speeding (*22*). Bicycle crash severity also has been found to increase in poor weather and in darkness with no streetlights *(22-23)*. Other studies have found that crash rates decrease as a function of levels of cycling participation, supporting the safety in numbers hypothesis *(24-28)*.

Role of rider characteristics in crash risk

Rider characteristics that have been examined in relation to crash and injury risk include gender, age, level of riding experience, purpose of riding, use of conspicuity aids, risk taking, perceived risk and helmet use. Some studies have examined the characteristics of other road users in multi-vehicle bicycle crashes (e.g. *22*). Bicycle riding is generally more popular amongst males than females and males often ride further, but after correcting for this, crash risk does not appear to differ by gender *(15-16)* and more severe injuries in males have been reported in some studies (*29-30*), but not others *(22)*. Among adult riders, age appears to have little effect on crash risk once distance ridden is taken into consideration *(15)* but the severity of injury appears to be greater for older riders *(15, 22)*.

Crash risk has been associated with cycling inexperience *(15, 16, 31)*. After adjusting for a range of demographic and exposure variables, Heesch et al *(16)* reported that injury risk was higher for riders who had ridden for less than 5 years as an adult, compared to riders who had ridden for 10 years or more.

Purpose of riding could possibly affect crash risk either directly or by influencing the location of riding but there is relatively little research into this factor. Cycling for recreation and cycling for competition were both associated with increased adjusted crash risk in an Australian study *(16)*. A Swedish study *(32)* found that bicycle injuries were three times more likely when riding for leisure purposes than when commuting.

There has been significant research into the contribution of lack of conspicuity of the rider to serious crashes and the use and effectiveness of conspicuity aids. Many studies have reported that the most serious injuries to bicycle riders occur in crashes involving motor vehicles. For example, Australian data has shown that less than 10% of injured cyclists in hospital emergency departments had collided with another vehicle *(33)* while 85% of cyclist fatalities resulted from collisions with motor vehicles *(34)*. Failure on the part of the motor vehicle driver to see and respond to the cyclist has contributed to the occurrence of many crashes. A British study *(35)* reported that 56% of serious cyclist crashes were attributable to other road users failing to look properly for cyclists (and 43% were attributable to cyclists failing to look properly for other road users). In addition, riders and pedestrians have been found to over-estimate their own visibility to car drivers *(36)*. Thus, measures to improve the conspicuity of cyclists are potentially very important in bicycle safety.

A Cochrane Review of interventions for increasing pedestrian and cyclist visibility *(37)* identified benefits of fluorescent yellow, red and orange clothing in improving daytime detection and recognition and lamps and flashing lights and retroreflective material in red and yellow for improving night-time visibility. A cross-sectional survey of riders in a New Zealand mass-participation event *(15)* reported that riders who always wore fluorescent colours had eight times fewer days off work from bicycle crash injury in last year compared to those who never wore fluorescent colours. The analysis controlled for age group, gender, average cycling speed, years of experience, involvement in bunch riding and distance ridden per year. Earlier studies of motorcycle crash risk also identified risk reductions associated with use of high visibility clothing *(38)*. The Cochrane Review *(37)* cautioned that there had been no randomised controlled trials of the effect of use of conspicuity aids on crash involvement and that the available research was confounded by potential differences in risk taking, riding locations, and riding times between users and non-users of visibility aids.

There is some evidence that risk taking and low levels of perceived risk on the part of bicycle riders contribute to crash risk. Riding under the influence of alcohol is associated with increased crash severity *(22)*. Rider violation of road rules has been found to contribute to some crashes but a recent analysis of police-reported bicycle-motor vehicle crashes found that riders were less often at fault than car drivers, although younger riders were more likely to be at fault *(39)*.

The perceived risk of cycling has been shown to influence whether people ride a bicycle *(40, 41)*. Among serious leisure cyclists, their perception of the risk of crashing was only a low to modest barrier to cycling and perceptions of risk were lower for those with more experience *(42)*. The Health Belief Model concepts of perceived susceptibility or vulnerability and perceived severity have been examined in studies of factors affecting the voluntary use of bicycle helmets *(43-45)*. Perceived susceptibility was correlated with helmet use and intention to wear a helmet by British schoolboys, but perceived severity was not *(43)*. In contrast, perceived severity was related to intention to use a bicycle helmet by Finnish teenagers, while perceived susceptibility was not *(44)*. Perceived danger of cycling and perceived severity of a crash were greater for helmet-wearers than non-helmet-wearers in a study of college students *(45)*.

Focus of this paper

A repeated finding in the research summarised above has been that many of the riding environment and rider characteristics affecting crash risk are inter-related. For example, Haworth and Schramm *(46)* found that experience, age, gender, distance ridden and purpose of riding were related. Gender *(47, 49, 50)* and degree of experience *(46, 48, 50)* influence route choice. This paper aims to better understand the complex relationships between bicyclist injuries resulting from crashes such as hitting a car or pedestrian, non-crash injuries such as spraining an ankle, and perceived risk of cycling. In addition to gaining insight into these relationships, the primary factors thought to influence injuries and perceived risks of cyclists are sought. The factors explored include metrics of cyclist exposure, rider conspicuity, riding environment, rider risk aversion, and rider ability. Given that within-rider injuries and perceived risk are correlated, a simultaneous equations approach is used to account for unobserved, within-bicyclist correlation. These insights and modelling approach to better understand bicyclist behavior serve as the primary and unique contributions of this paper.

The remainder of the paper first presents a section that describes the data collected for the study, describing the self-report survey data. The next section describes the methods used to analyse the survey data, briefly describing the seemingly unrelated regression approach. The results of the modelling are then discussed, followed by overall conclusions of the research.

DATA DESCRIPTION

Survey setting

This research was conducted in the State of Queensland, Australia. Queensland has about 4.5 million inhabitants, of which 2 million live in the capital city, Brisbane (*51*). The climate varies from sub-tropical to tropical, allowing year-round riding. Random population surveys have estimated that about 50% of adults in Queensland ride a bicycle at least once a month (*52, 53*). In the 2006 Census, 1.1% of Brisbane residents travelled to work by bicycle *(54)*, a figure comparable to that for Canada but higher than for the United States *(55)*. In Queensland it is legal for adults to ride a bicycle on the sidewalk and there is a mandatory helmet wearing law.

Survey Development and Recruitment

The information reported here was collected as part of a larger survey of the riding patterns, safety behaviors, perceived risks and injury experiences of Queensland cyclists which ran from October 2009 to the end of March 2010. The survey questions were based on national and international sources (*48-50*). Participants were recruited through advertising, media coverage, posting on cycling forums, distribution of promotional flyers and word of mouth. The questionnaire package (both online and hardcopy) included a cover letter and the questionnaire, and the hardcopy also included a reply-paid envelope. Participants who provided contact details to the research team were entered into a monthly prize draw for cycling accessories. Participants were required to be Queensland residents, and to have ridden a bicycle in the past 12 months. The majority of survey respondents were male (73%), with a median age of 41 years (range 18-78) and rode five days per week on average. The main purpose of riding was health or fitness, followed by commuting and then social or recreation. The project was approved by the Queensland University of Technology Human Research Ethics Committee.

Relevant Items and Coding

Table 1 lists the variables used in this analysis, and represents a subset of the overall data collection effort described previously. The variables were chosen and prepared specifically to support the study aims. The variable mnemonics are provided, along with a description of the survey question and categorical or continuous response categories. The presence of a variable in the table indicates that the research team believed *a priori* that some of these variables might be associated with cyclist injury or perceived risk, or both. In the subsequent section, many of the variables shown in Table 1 were not found to be statistically significant, and these findings are in some cases as important as findings of significance. Lack of significance findings are discussed later; however, it is important to note that Table 1 reflects an effort to capture measures of cyclist exposure, rider conspicuity, riding environment, rider risk aversion, and rider ability.

An injury was defined as any instance where the rider sought medical attention, or should have sought medical attention. Non-crash injuries were incurred through riding, but not falling off the bicycle or colliding with another road user or object. A crash injury was a result of a collision or falling off the bicycle. The mean numbers of crash and non-crash injuries reported over the past two years were similar (0.916 and 1.023).

Table 2 shows summary statistics—the number of complete observations, mean, standard deviation, minimum, and maximum values of the variables described in Table 1. For the analysis that follows, many of the variables in this table were coded into indicator variables as appropriate; however, the histogram statistics for the categorical equivalents are not shown here due to space limitations.

The outcome variables used in the analysis are derived from the observed variables shown in the previous tables. The variable *NCInjRate* is meant to capture injury risk associated with non-crash events such as muscle strains or injury to the eye, and is calculated as the ratio of *noncrashinj* to *distride*. The numerator is events per two years and the denominator is distance per week, so the units are in injuries per unit time. There is no need to calculate absolute risk in this study, and so relative risk comparisons suffice. The variable *CInjRate* is calculated as the ratio of *crashinj* to *distride* and is meant to capture the injury risk associated with crash events, such as falling off, colliding with pedestrians, other bicyclists, vehicles, or roadside objects. Finally, *RiskPerc* is meant to capture a cyclists' perceived risk of bicycling, and is measured on a 5 point scale with 1 being "much safer than driving" and 5 being "much less safe than driving"—thus increasing on the scale reflects increased perceived risk.

TABLE 1 Variables Used in Analysis: Responses from Self-Reported Bicyclist Behavior, Injuries, and Exposure

Variable Mnemonic	Description of variable and response categories
bikinhous	How many bicycles in working order are kept at your household? {0 to 9 as counts, 10 indicating 10 or more)}
mostoftbike	Bicycle ridden most often {0.00, no answer}{1.00, Childs}{2.00, Hybrid}{3.00,Noncomp Road}{4.00, Comp road}{5.00, Off Road}{6.00, Other}
replcost	How much would it cost to replace the bicycle (frame and bicycle parts, excluding accessories) you ride most often with a similar new bicycle? {1.00, Less than $150}{2.00, $150-300}{3.00, $301-500}{4.00, $501-800}{5.00, $801-1000}{6.00, $1001-3000}{7.00,$3001-5000}{8.00, $5001-10000}{9.00, More than $10000}{10.00, Don't know}
cyclskills	How would you describe your cycling skills? {1.00, Basic }{2, Competent}{3.00, Highly skilled}{4.00, Other}
exprider	New (riding in 2008 and/or 2009), Experienced (all 5 years), and Other {1.00, new rider}{2.00, experienced rider}{3.00, other}
daysride	How many days on average do you ride a bicycle in a week? {0.00, 0}{1.00, 1}{2.00,2}{3.00, 3}{4.00, 4}{5.00, 5}{6.00,6}{7.00, 7}
hoursride	What is the time (in hours) you spend riding in an average week?-
distride	What is the distance (in kilometres) you ride in an average week?-
footpthkm	What is the distance (in kilometres) you ride in an average week on footpaths?-
bikepthkm	What is the distance (in kilometres) you ride in an average week on bike paths?-
urbankm	What is the distance (in kilometres) you ride in an average week in urban areas?-
ruralkm	What is the distance (in kilometres) you ride in an average week in rural areas?-
propftpth	Calculated proportion of kilometres ridden on the footpath
propbkpth	Calculated proportion of kilometres ridden on the bicycle path
propur	Calculated proportion of kilometres ridden on the urban roads
proprural	Calculated proportion of kilometres ridden on the rural roads
propofrd	Calculated proportion of kilometres ridden on the off-road
avgspeed	What is your average travel speed (not including waiting for traffic or rest stops) when cycling? {1.00, Less than 16km/h}[2.00, 16-18.9 km/h}{3.00, 19-21.9 km/h}{4.00, 22-24.9km/h}{5.00, 25-32km/h}{6.00, more than 32km/h}{7.00, Don't know}
motiv	Primary motivation for riding {Utilitarian =1, Social =2, Health =3}
grprides	Do you participate in group (3 or more cyclists) rides?{1 = yes, 0 = no}
nitrides	Do you ride at night (after dusk or before dawn)?- {1 = yes, 0 = no}

TABLE 1 Continued

Variable Mnemonic	Description of variable and response categories
lowspd	When riding on the road, how often are you on roads with the following speed ...- 40-60km/h{1.00, Never}{2.00, Sometimes}{3.00, Mostly}
midspd	When riding on the road, how often are you on roads with the following speed ...- 70-80km/h{1.00, Never}{2.00, Sometimes}{3.00, Mostly}
highspd	When riding on the road, how often are you on roads with the following speed ...- 90-110km/h{1.00, Never}{2.00, Sometimes}{3.00, Mostly}
propbrtclth	Where you ride most often, what proportion of the time do you wear bright coloured clothing or accessories? {1.00, Never}{2.00,Rarely}{3.00, Sometimes}{4.00, Often}{5.00, Always, Almost always}
propflrclth	Where you ride most often, what proportion of the time do you wear fluorescent clothing or accessories? {1.00, Never}{2.00,Rarely}{3.00, Sometimes}{4.00, Often}{5.00, Always, Almost always}
proprflclth	Where you ride most often, what proportion of the time do you wear reflective clothing or accessories? {1.00, Never}{2.00,Rarely}{3.00, Sometimes}{4.00, Often}{5.00, Always, Almost always}
prophelmet	Where you ride most often, what proportion of the time do you wear a helmet? {1.00, Never}{2.00,Rarely}{3.00, Sometimes}{4.00, Often}{5.00, Always}
propfrntlit	When riding in reduced visibility conditions (darkness, fog, rain, etc.) where you ride most often, what proportion of time do you use a front light (steady or flashing) {1.00, Never}{2.00,Rarely}{3.00, Sometimes}{4.00, Often}{5.00, Always}{6.00, Not applicable}
proprearlit	When riding in reduced visibility conditions (darkness, fog, rain, etc.) where you ride most often, what proportion of time do you use a rear light (steady or flashing) {1.00, Never}{2.00,Rarely}{3.00, Sometimes}{4.00, Often}{5.00, Always}{6.00, Not applicable}
cyclperisk	Which statement best describes your opinion about the safety of cycling as a means of transport?{1.00, Cycling is much safer than driving a car}{2.00, Cycling is somewhat safer than driving a car}{3.00, Cycling is about as safe as driving a car}{4.00, Cycling is somewhat less safe than driving a car}{5.00, Cycling is much less safe than driving a car}
riskavoid	How would you describe your attitude to risk when cycling? {1.00, I try to avoid risk}{2.00, I don't think about risk}{3.00, I seek out risk}
noncrashinj	How many times in the past 2 years have you been injured while cycling without crashing (eg. muscle strain, foreign object in eye)? This does not include falling off the bicycle or colliding with something/someone. {count of injuries}
crashinj	How many times in the past 2 years have you been injured as a result of a crash (eg. being hit by a car, falling off your bicycle)? {count of injuries}
injevents	Calculated total number of injury events {crash plus non-crash injuries}
injlocation	{0, none}{1, Footpath}{2, bike path}{3, urban road with on-road bike facility}{4, urban road without on-road bike facility}{5, rural road}{6, off-road/trail}{7, track (velodrome/bmx)}{8, skate park}{9, urban/street scapes}{10, other}{11, home}{12, N/A}
hosptreat	Were you treated at hospital as a result of the injury? {1 = yes, 0 = no}
hospadm	Were you admitted to a hospital as a result of the injury? {1 = yes, 0 = no}

TABLE 2 Summary Statistics of Variables Tested for Significance in Modelling

Variable Mnemonic	Obs	Mean	Std. Dev.	Min	Max
bikinhous	2459	3.98	2.37	0	12
mostoftbike	2532	3.44	1.12	0	6
replcost	2307	6.16	1.63	1	10
cyclskills	2529	2.39	0.56	1	4
exprider	2516	2.06	0.68	1	3
daysride	2520	4.25	1.67	0	7
hoursride	2518	7.07	4.64	0	70
distride	2518	150.50	112.10	0	900
footpthkm	2087	3.45	11.05	0	200
bikpthkm	2087	24.20	37.11	0	300
urbankm	2087	88.02	93.77	0	825
ruralkm	2087	29.46	64.94	0	700
propftpth	2079	4.60	12.29	0	100
propbkpth	2077	22.28	27.54	0	100
propurb	2077	52.04	32.47	0	100
proprural	2078	13.98	25.66	0	100
propofrd	2078	5.84	15.07	0	100
avgspeed	2524	4.34	1.41	1	7
motiv	2532	2.10	0.91	1	3
grprides	2532	0.31	0.46	0	1
nitrides	2532	0.28	0.45	0	1
lowspd	2457	2.81	0.42	1	3
midspd	2350	1.96	0.62	1	3
highspd	2290	1.56	0.66	1	3
propbrtclth	2531	3.93	1.18	1	5
propflrclth	2520	2.47	1.44	1	5
propreflclth	2525	2.89	1.46	1	5
prophelmet	2532	4.99	0.15	1	5
propfrntlit	2525	4.78	0.91	1	6
proprearlit	2528	4.87	0.79	1	6
cyclperisk	2524	4.14	0.97	1	5
riskavoid	2526	1.08	0.29	1	3
noncrashinj	2532	0.92	1.80	0	11
crashinj	2532	1.02	1.52	0	11
injevents	2532	1.93	2.64	0	22
injloc	2532	2.72	2.61	0	10
hsptreat	2532	0.13	0.33	0	1
hspadm	2532	0.05	0.22	0	1

ANALYSIS METHODS

There are three outcomes of interest here - self reported injury risk resulting from crash and non-crash events as well as perceived risk, and because these outcomes were measured simultaneously from individuals in the sample, their outcomes are correlated, or potentially correlated, within individuals in the sample *(56)*. Interrelated systems of equations like the one examined here create a potentially serious estimation problem if their interrelated structure is ignored. This problem arises because ordinary least squares (OLS) estimation of model parameters violates a key OLS assumption requiring that the correlation between regressors and disturbances is essentially zero. This endogeneity or errors is problematic, and will result in erroneous conclusions and inferences if ignored. Although details are left to the interested modeller, estimation was conducted using three-stage least squares (3SLS), a popular and robust estimation approach for system equation models *(56)*.

In the modeling conducted here, two possibilities are considered. The first is that an outcome may serve as a predictor for another outcome. For example, non-crash injuries may be good predictors of crash related injuries, or perceived risk may serve as a good predictor of crash injury. In this approach endogenous variables (influenced by external variables) serve as predictors. Another possibility is that only exogenous variables serve as predictors. The second approach is called seemingly unrelated regressions, because none of the predictor variables are endogenous, and thus one might not recognize the obvious within subject correlation in the sample and resulting simultaneity *(56)*. The analyses conducted later found that the seemingly unrelated regressions best fit the self reported bicycle data, and thus are described here.

When studying the two injury risk outcomes (those resulting from crash and non-crash events) and perceived bicycling risk, the following equation system is written:

$$InjuryRate_{noncrash} = \boldsymbol{\beta}_{nc}\mathbf{Z} + \boldsymbol{\delta}_{nc}\mathbf{Y} + \boldsymbol{\alpha}_{nc}\mathbf{X} + \boldsymbol{\theta}_{nc}\mathbf{W} + \boldsymbol{\varphi}_{nc}\mathbf{V} + \boldsymbol{\varepsilon}_{nc} \quad (1)$$

$$InjuryRate_{crash} = \boldsymbol{\beta}_{c}\mathbf{Z} + \boldsymbol{\delta}_{c}\mathbf{Y} + \boldsymbol{\alpha}_{c}\mathbf{X} + \boldsymbol{\theta}_{c}\mathbf{W} + \boldsymbol{\varphi}_{c}\mathbf{V} + \boldsymbol{\varepsilon}_{c} \quad (2)$$

$$PerceivedRisk = \boldsymbol{\beta}_{pr}\mathbf{Z} + \boldsymbol{\delta}_{pr}\mathbf{Y} + \boldsymbol{\alpha}_{pr}\mathbf{X} + \boldsymbol{\theta}_{pr}\mathbf{W} + \boldsymbol{\varphi}_{pr}\mathbf{V} + \boldsymbol{\varepsilon}_{pr} \quad (3)$$

where *InjuryRate* reflects the rates for the non-crash and crash injuries, and *PerceivedRisk* reflect the outcome variables of interest. In these equations, **Z** is a vector of cyclist skill and ability attributes, **Y** is a vector cyclist conspicuity measures, **X** is a vector of riding environment influences, W is a vector of cyclist risk aversion, and **V** is a vector of cyclist exposure metrics. Finally, $\boldsymbol{\beta}, \boldsymbol{\delta}, \boldsymbol{\alpha}, \boldsymbol{\theta},$ and $\boldsymbol{\varphi}$ are vectors of estimable parameters, and $\boldsymbol{\varepsilon}$ are the correlated disturbance terms within individuals. Further details on three stage least squares estimation of this system of equations can be found in Washington et al *(56)* among other econometric references.

ANALYSIS FINDINGS AND DISCUSSION

The result of the seemingly unrelated regression estimation is shown in Table 3. Essentially, three separate linear regression equations are estimated simultaneously, each focused on a different outcome variable, defined previously as *NCInjRate*, *CInjRate*, and *RiskPerc*. The table shows the overall estimation results at the top, with number of observations, number of parameters, root mean squared error, R-square, Chi-square, and the P-value associated with a reduced model without any predictors. All three models are shown to be superior to models with simply a constant term, suggesting that the outcomes do vary as a function of various predictors. The body of the table shows the estimated parameters, standard errors, z values, and p-values associated with variables in the three bicyclist models. The parameters were estimated simultaneously using iterated three stage least squares. The model variables are discussed in detail in the remainder of this section. In the Discussion both included variables found to be statistically significant and variables omitted due to lack of significance are mentioned when appropriate. A 95% level of confidence was used throughout the modelling to retain and omit variables.

TABLE 3 Seemingly Unrelated Regression: Simultaneous Linear Regressions of Self-Reported Non-Crash Injury Rate, Crash Injury Rate, and Perceived risk of a sample of Bicyclists from Brisbane, Australia

Equation	Observations	Parameters	RMSE	R-square	Chi-square	P-value
NCInjRate	1884	7	.03684	0.0666	157.98	<0.0001
CInjRate	1884	7	.06395	0.1207	312.00	<0.0001
RiskPerc	1884	7	.94589	0.0461	90.89	<0.0001
Non-crash Injury Rate	**Coefficient**	**Std Error**	**Z**	**P>|z|**		
daysride	-.0015969	.000553	-2.89	0.004		
replcost	-.0013743	.0005875	-2.34	0.019		
avgspd_2	.0094144	.0032267	2.92	0.004		
propfrntlit_1	-.0092742	.0045794	-2.03	0.043		
propurb	-.0000564	.0000248	-2.27	0.023		
constant	.0281494	.0040005	7.04	<0.001		
Crash Injury Rate	**Coefficient**	**Std Error**	**Z**	**P>|z|**		
daysride	-.002507	.0005818	-4.31	<0.001		
replcost	-.001468	.0006299	-2.33	0.020		
propftpth	.0001846	.0000728	2.54	0.011		
prophelmet_5	-.0554315	.0098659	-5.62	<0.001		
injloc_7	.024576	.0027493	8.94	<0.001		
constant	.0835026	.010705	7.80	<0.001		
Perceived risk	**Coefficient**	**Std Error**	**Z**	**P>|z|**		
daysride	-.0435874	.0141963	-3.07	0.002		
propbkpth	-.0029014	.0008774	-3.31	0.001		
motiv_1	-.2861477	.0508835	-5.62	<0.001		
grpride_1	.147994	.0548454	2.70	0.007		
highspd_2	.1206922	.0501616	2.41	0.016		
prophelmet_5	.6607178	.2657628	2.49	0.013		
propfrntlit _5	.1419381	.0550192	2.58	0.010		
constant	3.643714	.2745082	13.27	<0.001		

*variable*_1 is the first categorical response indicator of *variable*. For example, avgspd_1 is an indicator for average travel speed less than 16 km/hr (see Table 1).

Endogeneity

Endogeneity was tested in all of the models and was not found to be statistically significant. For example, the outcome variables may serve as predictors in the remaining models, so crash injury risk might influence perceived cycling risk on the grounds that a cyclist who crashes may perceive cycling to be a higher risk activity (compared to a cyclist who has not crashed). Again, endogeneity was not found in any of the models.

Cyclist Exposure

The classical exposure variables in the models include days per week of riding (*daysride*) and proportion of urban kilometers (*urbankm*). Increasing exposure by riding more days per week is associated with a reduction the risk of both crash and non-crash injuries per kilometre travelled. Moreover, increasing exposure is associated with a reduction in perceived risk of bicycling, as it is for car driving *(57)* and motorcycling *(58)*. There are numerous plausible explanations for this finding with bicyclists. First, it is quite possible that there is a fairly steep learning curve with cycling due to the requirement for fitness and hand-eye coordination. As a result, novice riders are confronted with obstacles and dangers that lead to injuries. Second, unlike driving a motor vehicle, bicyclists must remain vigilant and generally cannot attempt to multi-task and become distracted by mobile phones, etc. Third, bicyclists may retain and develop a sense of vulnerability (perceived risk) associated with cycling that is not so strongly associated with vehicular travel. All of these plausible explanations are conjecture and require testing and validation.

Rider Conspicuity

Rider conspicuity variables include the use of lights and bright coloured clothing, although the clothing variables were not statistically significant in any of the models. In the non-crash injury model, *propfrontlit_1* (a rider reporting that they **never** use a front bicycle light) is associated with a reduction in the injury rate. It is presumed that this variable is capturing riders who do not ride at night, when visibility is less and non-crash injury risk is increased. As such, the non-use of a light is likely correlated with an omitted variable. It is left in the model as a point of further research and analysis, and to highlight possible omitted variables that should be captured in future research. Recall that non-crash injuries include sprains, etc., that are not the result of a crash. In the perceived risk model, the variable *propfrntlit_5* (a rider reporting that they **always** use a front bicycle light) is associated with an increase in perceived bicycling risk. This suggests that riders compensate for increased perceived risk by using a front bicycle light. Note, however, that this variable is not significant in either of the injury risk models.

Riding Environment

Statistically significant riding environment variables in the models include the proportion of riding on bike paths, the proportion riding on foot paths (sidewalks), riding in high speed environments, and worst injury location. In the non-crash injury model, increasing the proportion of riding on the footpath is associated with an increase in non-crash injury risk—likely the result of riding on infrastructure not designed for the relatively higher speeds and clearances needed for cycling. Riders who sometimes ride in high speed environments perceive greater risk of cycling. In the crash injury rate model, riders who reported their worst injury occurred in a velodrome (*injloc_7*), indicating a fairly serious cyclist, had higher crash injury rates. Riders who compete enter environments that are of higher risk, not unlike car racing, and thus reveal on average increased crash risk.

Rider Risk Aversion

Rider risk aversion is thought to be confounded to some extent with rider conspicuity. Variables intended to capture rider risk aversion (or perception) included helmet wearing, riding in high speed environments, replacement cost of a bicycle, and a question regarding risk avoidance (*riskavoid*), which was not statistically significant in any of the models. The influence of helmets was revealed in two of the models, and was absent (not statistically significant) in the non-crash injury rate model—which serves both to validate that non-crash injuries should not be influenced by helmet use and to lessen the likelihood of the helmet use variable in other models suffering from spurious significance. Riders who reported **always** wearing a helmet (*helmet_5*) are associated with a reduction in crash injury risk and an increase in perceived risk of cycling. This finding presents strong evidence that the perception of cycling risk is balanced by the inclination to always wear a helmet. Moreover, it strengthens the evidence in support of reduced crash injury risk when helmets are worn. Wearing a helmet is almost 5 times more effective at reducing crash injury risk than always using a front light, according to the model.

Average speed is significant only in the non-crash injury rate model. Riders who reported riding on average less than 16 km/h were associated with a reduction in non-crash related injuries.

The replacement cost of a bicycle is postulated to reflect a crash disincentive. The underlying logic is that the more expensive a bicycle, the more effort a rider will undertake to avoid crashing. Expensive bicycles can cost more than AUD$10,000, and some may not be insured. Statistically significant effects of bicycle replacement costs (*replcost*) were revealed in both crash risk models—supporting the hypothesis that higher cost bicycles are associated with lower crash and non-crash injury risk. The elasticity of effect is higher for crash injury risk compared to non-crash injury risk, suggesting perhaps that non-crash events are more difficult to consciously avoid (pulling a muscle, etc.) than crash events.

Rider Ability

Rider ability, or type, is captured by variables describing a rider's motivation for riding and whether a rider engages in group rides—an indicator of refined riding skill necessary to cycle closely among other riders. Riders who reported riding for utilitarian purposes (e.g. going to work or shopping, *motiv_1*) have a lower perceived risk of cycling compared to riders with other purposes. This might be explained by the fact that this cycling motivation may not reflect discretionary travel compared to cycling for health of for social reasons—thus there is somewhat limited choice and utilitarian riders may dismiss the risk. Alternatively, these riders may not perceive cycling risk as high (for whatever reasons) and thus engage in utilitarian travel as a result, willing to undertake regular utilitarian travel using this non-risky mode of travel. Riders who never engage in group rides (*grpride_1*), an activity that requires a relatively high degree of riding skill, were associated with increased perception of cycling risk.

Survey limitations

There are a number of limitations relating to the characteristics of participants, where the research was conducted and the way in which data items were presented and analysed. Compared with population representative samples collected in Queensland, the survey respondents rode more often and longer than other cyclists (*20, 21*). Thus they may not be reflective of the general cycling population. It may be beneficial for future research to actively target areas used for recreational cycling (suburban parks and bikeways), and less specialised bicycle retailers (including department stores) to increase the representation of recreational cyclists in surveys.

The survey specifically excluded riders aged less than 18 years. Child cyclists are an important focus for research because almost 75% of all injured cyclists presenting to hospital emergency departments in Queensland are under 15 years of age (*33*). Future research is required to examine the riding, safety and injury patterns of child cyclists.

Caution needs to be taken in generalising the results from this survey to other cities and countries. Compared to other parts of the world, Queensland may have relatively poor facilities on urban roads and some of its bicycle paths provide well-surfaced and useful alternatives to urban roads. In addition, the amount of sidewalk riding may be higher because the study was conducted in a jurisdiction where it is legal.

CONCLUSIONS

This paper aimed to better understand bicycle crash risk and perceptions of risk from self reported behavior of a sample of cyclists in Queensland, Australia. The focus was to examine the role of cyclist exposure, rider conspicuity, riding environment, rider risk aversion, and rider ability and their potential influences on crash and non-crash risk as well as perceived risk.

The major findings suggest that perceived risk does not appear to influence injury rates, nor do injury rates influence perceived risks of cycling. Riders who perceive cycling as risky tend not to be commuters, do not engage in group riding, tend to always wear mandatory helmets and use front lights, and have lower perception of risk with increased days per week of riding and increased riding proportion on bicycle paths. Riders who always wear helmets have lower crash injury risk. On a days per week of riding basis, increased riding is associated with decreased injury and non-crash injury risk.

The risk of non-crash injury was similar to that of crash injury. This suggests that to prevent injuries to cyclists, it may be necessary not to focus solely on crash reduction, but to expand education to include bicycle set-up, bicycle skills, and understanding the demands of physical activity.

The results support the extensive literature that has demonstrated the crash injury reduction benefits of helmet wearing (reviewed in *59*) and show that these benefits are about five times greater than using a front bicycle light. Those who always wore a (mandatory) helmet had an increased perception of cycling risk, suggesting that legislation and enforcement may need to be supplemented with information about the risks of cycling. This may not be palatable, however, for those whose primary aim is to increase cycling participation.

Not all of the measures to improve rider conspicuity affected injury risk. Use of rear lights was not associated with crash or non-crash injury risk or perceived bicycling risk. This conflicts with experimental studies of conspicuity (*37*) and crash data that show many cyclists being seriously injured or killed by motor vehicles approaching from the rear (*34*). It may be that the low overall severity of self-reported crashes in this sample means that not many of the crashes where rear lights could be beneficial were included.

While this analysis revealed some new relationships among crash risk and perceived risk and reinforced some previous findings, improvements to the analysis are possible. First, the major factors thought to influence cycling crash risk and perceived risk, such as *rider conspicuity*, may be thought of as latent variables measured by a set of questions. In this case the entire analysis may be repeated using a structural equation modelling approach. While simultaneous equations and structural equations models (SEM) are closely related, a fundamental difference is the introduction of a latent (unobservable) construct in the SEM framework. The introduction of latent variables combined with testing of hypothesis around relationships with crash risk and perceived risk may reveal additional insights not possible through this analysis; and as such remains a topic of potential future research.

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